Research Studies on the Design of External Stimuli Responsive Devices using Additive Manufacturing

Synopsis

submitted in the partial fulfilment for the requirement of

Doctor of Philosophy

in

Mechanical Engineering

Submitted by

Abhishek Raj

Under the supervision of

Dr. Rahul Swarup Sharma
Professor

Under the Co-Supervision of

Dr. Ankit Sahai
Associate Professor

Department of Mechanical Engineering, Faculty of Engineering

Dayalbagh Educational Institute (Deemed University)

Dayalbagh, Agra (UP) – 282005

2023

Introduction

Additive Manufacturing

As technology has evolved, Additive Manufacturing (AM) techniques are now widely employed in manufacturing industries to connect and boost productivity. The process or technologies of AM represent the future of manufacturing [1]. AM processes are more efficient and quicker than others because they can produce complex geometry feature parts with less material waste and no need for fixtures [2]. There are seven overall categories of AM [3]. One of them is Material Extrusion (ME) [4], which is a technique that deposits a continuous strand of composite or thermoplastic Material to manufacture three-dimensional (3d) objects layer by layer [4].

External Stimuli Responsive devices

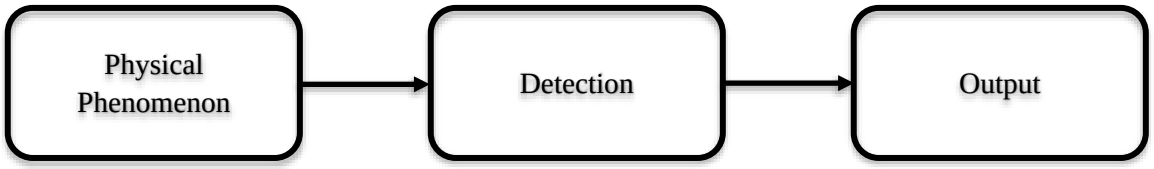

Figure 1: Working of ESR Device

An External Stimuli-Responsive (ESR) device detects the physical input from the surroundings and reacts to it, as shown in Figure 1. Light, heat, motion, moisture, and pressure are environmental phenomena considered for the input [5]. In the most general form, ESR devices are systems with various components. Three essential components have already been identified: an element, packaging and connections, and ESR signal processing hardware figure 1. ESR finds application in almost every engineering field. ESR devices are utilized in various industries, including the biomedical, agricultural, chemical, food, metal production, mechanical, electrical, shipping, and space sectors, like ISRO (Indian Space Research Organization), NASA (National Aeronautics and Space Administration), and ESA (European Space Agency). Essentially, ESR devices are used in all facets of human life [6].

However, with the conventional process comes a disadvantage: Customizable and flexible ESR devices cannot be produced quickly. Also, there is no application as a structural component, and to manufacture ESR devices using a conventional technique, significant capital, machinery, and a highly controlled environment are required. It is not possible everywhere for everyone, and still, with the

traditional process, customizable and flexible ESR cannot be produced if it is; the cost is so high that they cannot survive in the market.

The suggested research endeavor is to standardize and improve the ME process for ESR devices. The proposed experiment entails creating and fabricating a substance with the necessary components and proportions in the mixture to fabricate ESR devices with the required characteristics, such as size, shape, and capacity. In the proposed work, ESR devices will be created using a ME system; materials for fabrication come in various ratios, including the packaging of ESR, which will be of different polymer materials according to the application.

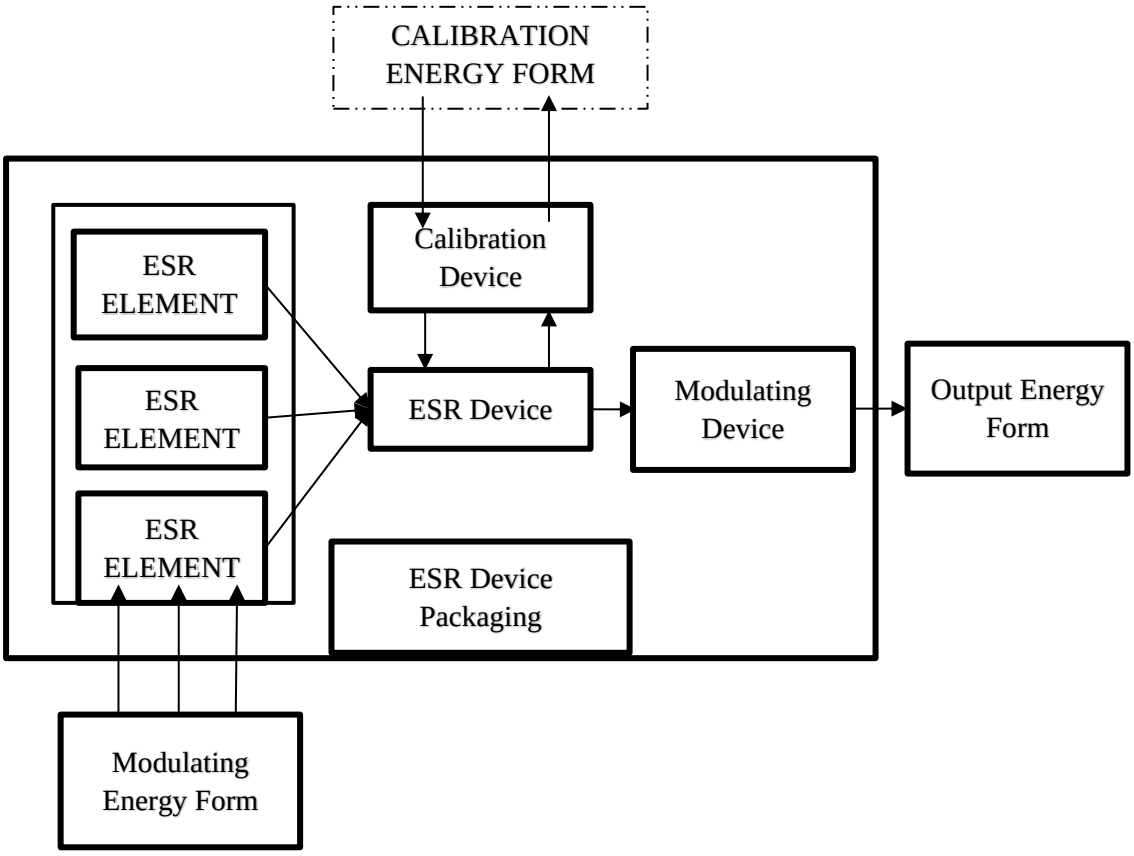

Figure 2: Anatomy of ESR devices

Development of functional ESR devices for the following two applications:

1. Piezoresistive flexible External Stimuli-Responsive (ESR) for pressure point measuring in bio-medical applications such as socket and amputee interface.

2. Tactile (Flex) External Stimuli-Responsive (ESR) in biomedical applications such as artificial hand fingers.

Various ESR devices, including temperature SR devices, are mainly used to detect the temperature of the environment where they are placed. For example, the devices used to measure body temperature and pressure SR devices find their main application in measuring oil pressure and brake pressure. Force-responsive devices find use in the medical industry, like dialysis machines, endoscopic surgery, physical therapy equipment, orthopedics, and MRI devices. Other ESR devices include position, vibration, piezo, fluid property, humidity, strain gauges, photo optics, flow, and level switches. But they all come with the limitation of a lower degree of freedom.

Literature review

The performance of many devices may be significantly enhanced by having more freedom in their possible geometry, which is achievable through the ME process. Health monitoring systems have generated much interest recently because of the numerous potential applications in preventative medicine. Flexible SR devices (both wearable and implanted) that can detect and measure various biological signals are human-interactive health monitoring technology. Prior attempts at measuring human movement have been effective when utilizing piezoresistive strips made from carbon nanotubes[7]. Considerable effort has been made to create innovative sensing materials, inventive macrostructures, and manufacturing processes to quickly create flexible force-responsive devices [8].

ESR devices found applications throughout the industrial revolution, as depicted in Figure 3, starting from the 18th century to the current time. ESR development began with Industry 1.0, a mechanical transducer that acts as an indicator but cannot show actual value. They are also large compared to smart ESR, like inline oil quality ESR in the Industry 4.0 revolution that can deliver actual values.

Micro Electro Mechanical Systems (MEMS) technology creates commercially available ESR devices.[5] Utilizing a concept known as Microsystems Technology (MST), MEMS are tiny integrated devices that combine electronic, electrical, and mechanical components to fulfill a single functional requirement [5].

The MOSFET (Metal-Oxide-Semiconductor field-effect transistor), created by Mohamed M. Atalla and Dawon Kahng in 1959 and demonstrated in 1960, is the precursor to metal-oxide-semiconductor (MOS) technology [9] Later, MOSFET ESRs were created, and they are now frequently employed to measure environmental, biological, chemical, and physical factors [10].

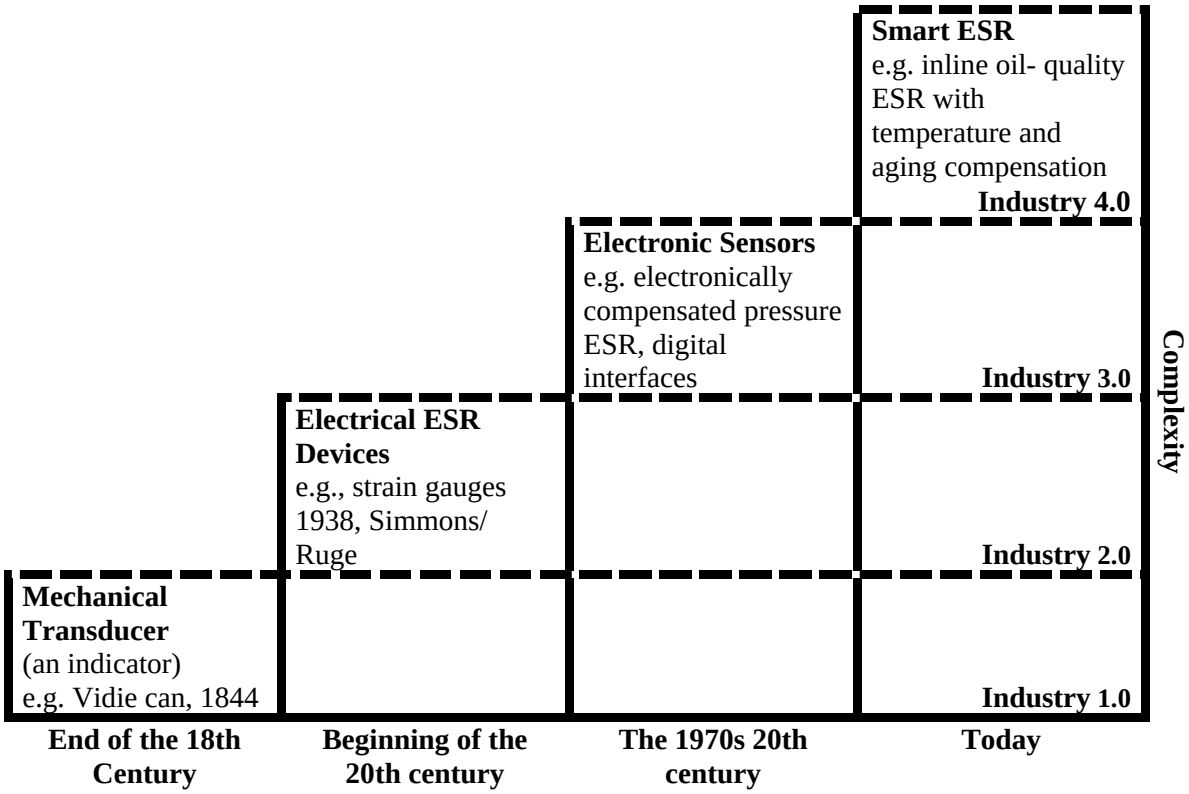

Figure 3: Historical Evolution

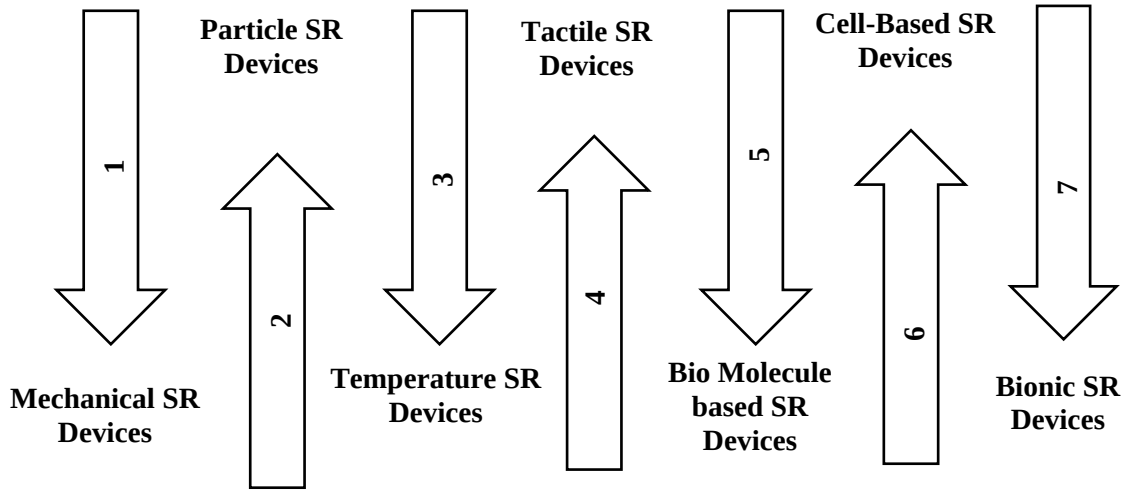

Figure 4: Main groups of AM ESR based on the usage

Table 1: Information on AM-printed ESR Devices

Method	Material	Application of ESRs	Transduction Mech.	Ref.
LOM	Silicone rubber	Strain ESR	Resistance	[11]
FFF	Carbamorph	Pressure	Capacitance	[12]
	ABS-based Material	Compression loading	capacitance	[13]
	PVDF	Biosensing part	capacitance	[14]
	ABS	Pressure	Optical absorbance	[15]
	PC	Tactile ESRs	Capacitance	[16,17]

	Nd-Fe-B magnets	Displacement ESR	Hall Effect	[18]
	Plastic	Angular ESR	Hall effect	[19]
	PLA	Acoustics and Ultrasonics ESRs	Frequency distribution	[20]
	VisiJet® EX 200 & S100	Electromagnetic ESR	Inductor-capacitor (LC)	[21]
	PLA, ABS	EEG ESR	Resistance	[22]
	PLA	EEG ESR	Resistance	[19]
	Dupont 5064H	Antennas	RF reception	[23]
	Polylactic acid (PLA)	Chemo ESR	ECL	[24]
	VisiJet® EX 200 & S100	ESR for food quality	Electrochemical	[25]
	Magnetite nanoparticle	Flow ESR	Hall effect	[26]
DIW	VeroBlue RGD840	Strain ESR	Capacitance	[27]
	Graphene aerogel	Strain ESR	Resistance	[28]
	Silver nanoparticle ink	Antennas	RF Reception	[29]
	PDMS, Hydrogel	Biosensing ESR	Resistance	[30]
	Graphene/methyl-red	Humidity ESR	Resistance	[31]
PolyJet	SunTronic Jet Silver	Eddy's current position ESR	Inductance	[32]
	ANP ink and PVP	Humidity sensing	Capacitance	[33]
	Suntronic Jet Silver	Angular ESR	Capacitance	[34,35]
	MED610 polyjet ink	Acoustics and Ultrasonics ESR	Capacitance	[36]
	Photopolymer	Optical ESRs	Optical metrology	[37]
	DM 8515 Grey 35	Optical ESRs	Optical intensity	[38]
	MED610 polymer	Optical ESRs	-	[39]
	Nanosilver or copper ink	Magnetic Field ESRs	Resistance	[40]
	Visijet M3 crystal	Gas Detection ESR	Resonant frequency	[41]
Inkjet Printing	Silver nanoparticle ink	Humidity and temperature	Resistance	[42]
	UTDAg silver nano ink	Antennas	Patch antenna	[43]
	Exfoliated graphite and latex solution	Temperature	Resistance	[44]

Because conventional manufacturing technology is rigid, it does not allow for customizable and flexible ESR device production [45], requiring other technologies, one of which is the ME Process [1]. Over the years, various approaches have been made to make ESR devices using ME, with everyone having different methods. The various ESR devices that can be produced using ME are illustrated in figure 4.

Figure 5 depicts the scope of Additive manufacturing for fabricating the different types of ESR devices. Various types of research have been done over the years to develop ESR using AM Table 1.Y. L. Park, B. R. Chen, and R. J. Wood [11] refer a method for Resistance based ESR device produced using Laminated Object Manufacturing (LOM). Helisys Inc first created the AM method known as LOM.[46] The AM media used by LOM technology is adhesive-coated paper, plastic, or metal laminates. Layer by layer, these sheets of material are bonded together, then shaped with a knife or a laser [46]. The ESR device prototype was fabricated using a layered molding and casting process

[11]. Then, using two syringes, EGaIn (eutectic gallium indium) [12] was injected into the microchannels, which is time-consuming and depends on the molding and casting processes. This study proposes an alternative to this process, which includes a research study on printing silicone bases and its substitute using the material extrusion technique [4]. Then conductive inks filled in the microchannels simultaneously, which allows the free hand to customize the structure of the ESR device efficiently and effectively.

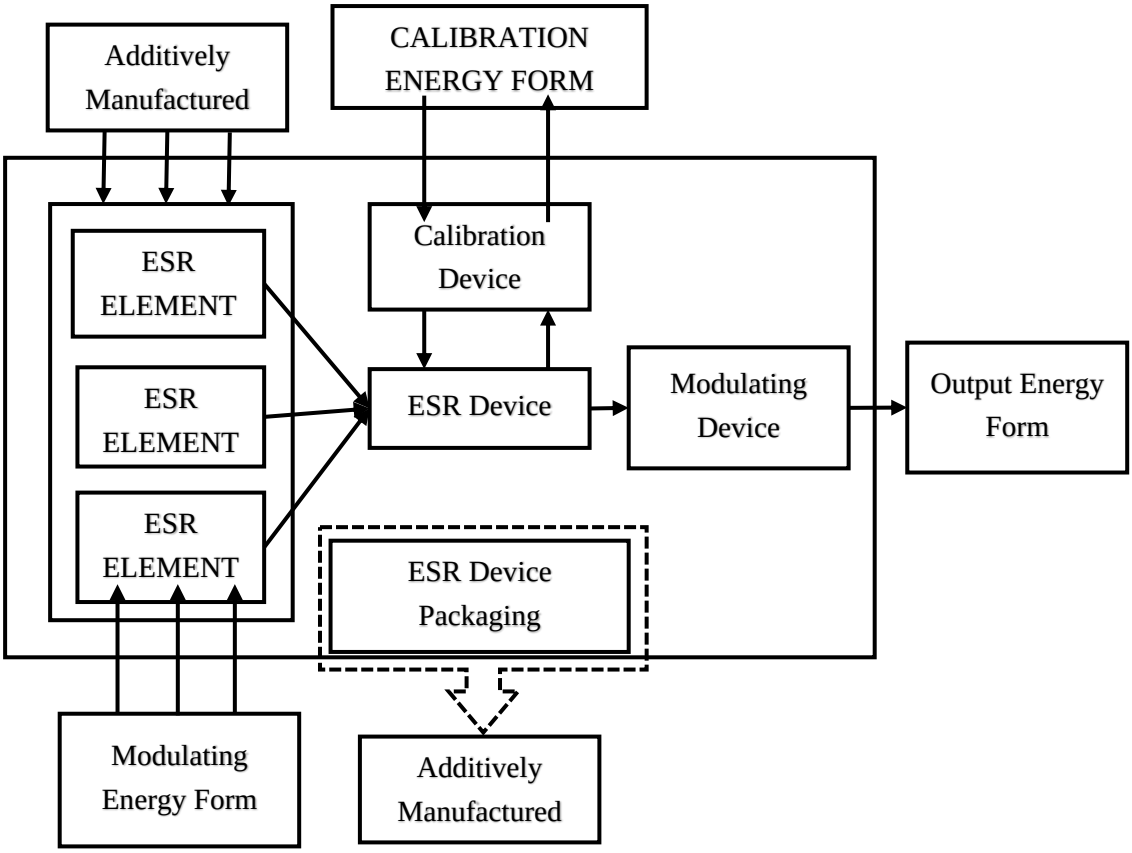

Figure 5: Anatomy of ESR devices and parts of it that can be manufactured using ME.

Fused Filament Fabrication (FFF)

In the process of FFF, thermal plastic filaments are deposited in a predetermined pattern using the melt extrusion technique [47] The FFF-based works in Table 1 are primarily rigid, which means they can provide customized but not flexible ESR, while the methods come with the advantage of easy availability and with a wide variety of materials [17]-[31].

Direct Ink Writing (DIW)

AM technology builds 3D structures by continuously raising the print head while depositing materials layer-by-layer [48], [49].

PolyJet Printing

Advanced AM technology called PolyJet creates parts, prototypes, and tooling that are exact and smooth. It can produce thin walls and complicated geometries using the broadest range of materials currently possible with any technology, with microscopic layer resolution and precision down to 0.014 mm [50].

Inkjet Printing

A low-temperature, low-pressure technology called 3D inkjet printing uses the deposition of liquid substances or solid suspensions [51]. This technique is suitable for various materials since it may deposit polymers, dielectric nanoparticles, and conductive nanoparticles. In this procedure, a tiny nozzle inside a print head extrudes the printing substance. Multiple layers are built once the print head raster scans over a surface [51].

No doubt DIW [48], [49], PolyJet [50], and Inkjet printing [51] have an advantage over the FFF process for their high-quality part production and use of materials in the form of resins and conductive ink [32]-[49] make ESR device element formation effective. However, when it comes to availability, these processes are not economical for sure, which gives FFF an advantage over this process; all the ESR mentioned in table 1 under DIW [48], [49], PolyJet [50] Inkjet printing [51] uses Material that is mostly either capable of fabricating ESR elements but not the whole ESR, including packaging. So, the proposed work is focused on developing an ME process capable of fabricating the entire ESR including its Element, transduction mechanism, and packaging as well as the real-life applications as flexible and customizable ESR devices. For the proposed work ME setup needs to be developed For Flexibility, materials are Silicone [7], Thermoplastic Polyurethanes (TPU) [8] for rigidity Poly Lactic Acid (PLA) [9], Acrylonitrile Butadiene Styrene (ABS) [10], and the other part is the ESR element. Transduction Mechanism going to be achieved using conductive inks like carbon nanotube inks, copper inks, carbon graphene inks [11], and eutectic gallium indium inks [12], [13]. These links are going to be used to make different patterns with different packaging to get the most efficient ESR.

Objectives

1. Design and development of a Material Extrusion experimental setup to investigate the effect of various process parameters in developing ESR devices.

2. Development of functional ESR devices using the aforementioned experimental setup.
3. Pilot scale demonstration of developed ESR device via Material Extrusion Additive Manufacturing.

Methodology

1. A thorough examination of the literature on the most current advancements in ESR devices and the ME process is for better comprehension and comparative analysis.
2. Design and Development of Material Extrusion based Experimental setup for fabrication of ESR devices.
3. Research into various ME printable materials, such as conductive inks and polymeric composites, for making ESR devices. Various thermoplastic materials, such as poly lactic acid, acrylonitrile butadiene styrene, and silicone, as well as conductive materials, such as carbon nanotube inks, copper inks, carbon graphene inks, and eutectic gallium indium, are included in the polymer composites.
4. Testing out various conductive material types.
5. Making ESR devices from the individual components, such as the base that holds the conductive element in place between its layers.
6. Extensive testing of manufactured parts comprises electrical testing (such as load and ionic conductivity), surface morphology (like fractography using scanning electron microscopy and x-ray photoelectron spectroscopy), chemical testing (such as environmental, abuse, and stability test), static testing, dynamic testing, and mechanical testing (such as tensile, compression, and impact test).
7. Study and analysis for effects of controllable process parameters of ME process on mechanical, chemical, electrical, and surface properties.

Likely impact of the research work

The improvement and standardization of the ME Process for ESR devices are going to be the main goals of the proposed research. As a result, India will become independent in ESR device AM. The study will mark a new turning point in India's growth and innovation and a significant accomplishment for the Make in India initiative. The results of the proposed work will surely encourage making the

technology affordable and adaptable so that it may flourish in the Indian market, making it an excellent job facilitator and encouraging the development of start-ups and entrepreneurs in India. Research and development are needed to look at new ME setup designs and fabrication process parameters to produce ESR devices at high throughput and cheap costs. It will offer a native assortment of affordable, custom-made ESR devices for various uses, including the biomedical industry, agroecology, aircraft electronics, electronic spacecraft, and satellite components.

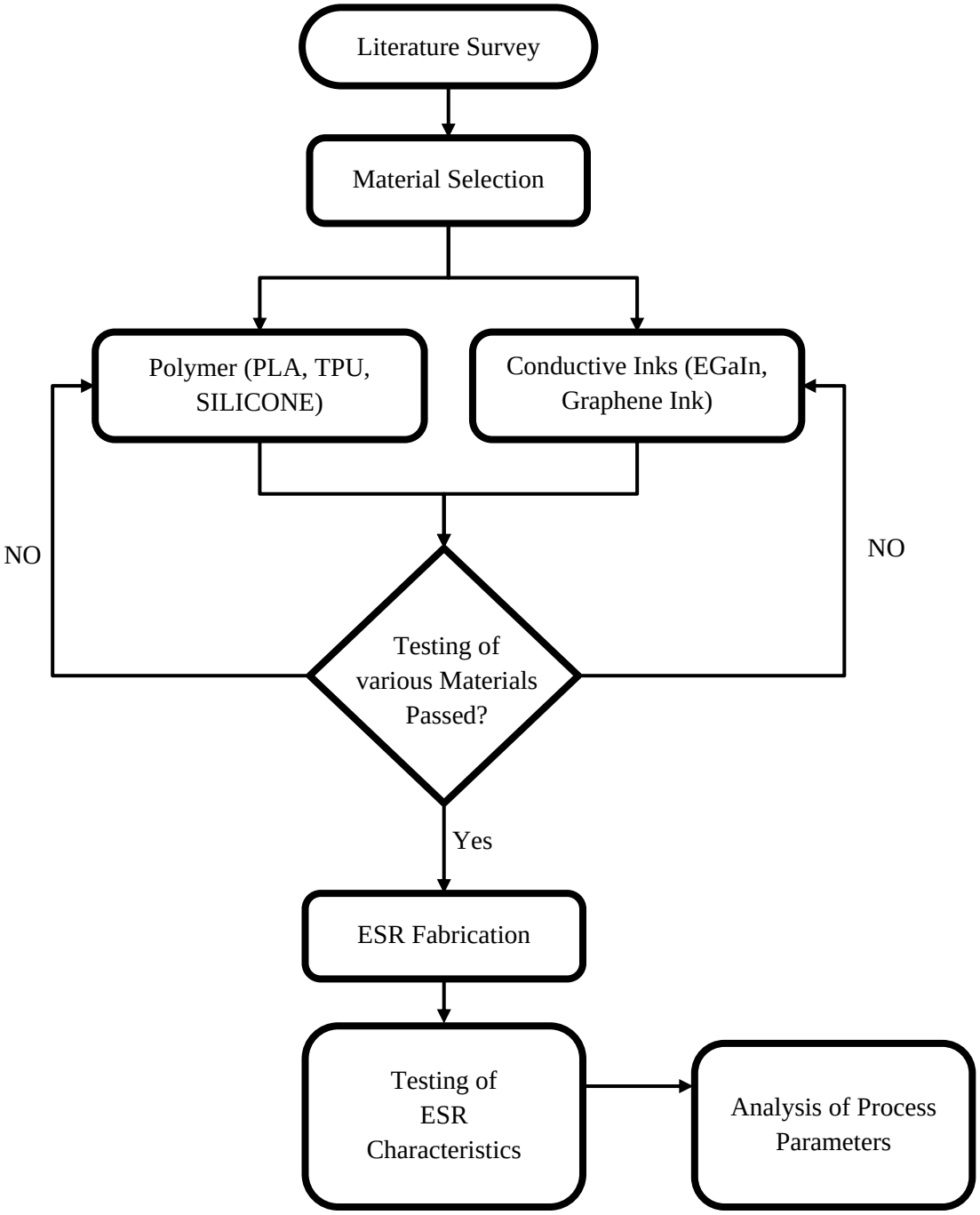

Figure 6: Work Flow Chart

Expected output and outcomes of the research work

(i) The proposed research and experimental activities will produce innovative ideas for pilot-scale ESR device demonstrations.

(ii) Understanding the influence of process variables from Material preparation through the ME process of the ESR devices is anticipated to open up possibilities for customization and simplicity of use at a lower cost.

(iii) The proposed technique will make it possible to fabricate complicated ESR device designs precisely controlled in size and shape.

(iv) By incorporating the ME Process, India will become less reliant on the global market and more independent in the ESR devices industry.

(v) Patent applications and high-impact journal publications.

References

[1] T. D. Ngo, A. Kashani, G. Imbalzano, K. T. Q. Nguyen, and D. Hui, "Additive manufacturing (3D printing): A review of materials, methods, applications and challenges," Compos B Eng, vol. 143, pp. 172–196, Jun. 2018, doi: 10.1016/j.compositesb.2018.02.012.

[2] D. José Horst and R. de Almeida Vieira, "Additive Manufacturing at Industry 4.0: a Review Fuzzy logic supporting decision making View project," 2018. [Online]. Available: www.erpublication.org

[3] T. D. Ngo, A. Kashani, G. Imbalzano, K. T. Q. Nguyen, and D. Hui, "Additive manufacturing (3D printing): A review of materials, methods, applications and challenges," Compos B Eng, vol. 143, pp. 172–196, Jun. 2018, doi: 10.1016/j.compositesb.2018.02.012.

[4] G. D. Goh, Y. L. Yap, H. K. J. Tan, S. L. Sing, G. L. Goh, and W. Y. Yeong, "Process–Structure–Properties in Polymer Additive Manufacturing via Material Extrusion: A Review," Critical Reviews in Solid State and Materials Sciences, vol. 45, no. 2, pp. 113–133, Mar. 2020, doi: 10.1080/10408436.2018.1549977.

[5] Administrator, "What are MEMS Sensors? Types, Applications." https://www.electronicshub.org/mems-sensors/ (accessed Aug. 12, 2022).

[6] M. Javaid, A. Haleem, S. Rab, R. Pratap Singh, and R. Suman, "Sensors for daily life: A review,"

Sensors International, vol. 2, p. 100121, 2021, doi: 10.1016/j.sintl.2021.100121.

[7] M. Cheng et al., “A review of flexible force sensors for human health monitoring,” J Adv Res, vol. 26, pp. 53–68, Nov. 2020, doi: 10.1016/j.jare.2020.07.001.

[8] D.-H. Kim, R. Ghaffari, N. Lu, and J. A. Rogers, “Flexible and Stretchable Electronics for Biointegrated Devices,” Annu Rev Biomed Eng, vol. 14, no. 1, pp. 113–128, Aug. 2012, doi: 10.1146/annurev-bioeng-071811-150018.

[9] Computer History Museum, “1960: Metal Oxide Semiconductor (MOS) Transistor Demonstrated.” https://www.computerhistory.org/siliconengine/metal-oxide-semiconductor-mos-transistor-demonstrated/ (accessed Aug. 12, 2022).

[10] H. Sood, V. M. Srivastava, and G. Singh, “Advanced MOSFET technologies for next generation communication systems - Perspective and challenges: A review,” Journal of Engineering Science and Technology Review, vol. 11, no. 3. Eastern Macedonia and Thrace Institute of Technology, pp. 180–195, 2018. doi: 10.25103/jestr.113.25.

[11] Y. L. Park, B. R. Chen, and R. J. Wood, “Design and fabrication of soft artificial skin using embedded microchannels and liquid conductors,” IEEE Sens J, vol. 12, no. 8, pp. 2711–2718, 2012, doi: 10.1109/JSEN.2012.2200790.

[12] S. J. Leigh, R. J. Bradley, C. P. Purssell, D. R. Billson, and D. A. Hutchins, “A Simple, Low-Cost Conductive Composite Material for 3D Printing of Electronic Sensors,” PLoS One, vol. 7, no. 11, Nov. 2012, doi: 10.1371/journal.pone.0049365.

[13] M. Saari, B. Xia, B. Cox, P. S. Krueger, A. L. Cohen, and E. Richer, “Fabrication and Analysis of a Composite 3D Printed Capacitive Force Sensor,” 3D Print Addit Manuf, vol. 3, no. 3, pp. 137–141, Sep. 2016, doi: 10.1089/3dp.2016.0021.

[14] E. Suaste-Gómez, G. Rodríguez-Roldán, H. Reyes-Cruz, and O. Terán-Jiménez, “Developing an ear prosthesis fabricated in polyvinylidene fluoride by a 3D printer with sensory intrinsic properties of pressure and temperature,” Sensors (Switzerland), vol. 16, no. 3, Mar. 2016, doi: 10.3390/s16030332.

[15] Y. Qin, Q. Wang, D. Xu, J. Yan, and S. Zhang, “A fiber Bragg grating based earth and water pressures transducer with three-dimensional fused deposition modeling for soil mass,” Journal of

Rock Mechanics and Geotechnical Engineering, vol. 14, no. 2, pp. 663–669, Apr. 2022, doi: 10.1016/j.jrmge.2021.07.009.

[16] Sensors Council, Annual IEEE Computer Conference, Md. IEEE Sensors Conference 12 2013.11.03-06 Baltimore, and Md. IEEE Sensors Conference 12 2013.11.04-06 Baltimore, IEEE sensors, 2013 3-6 Nov. 2013, Baltimore, Maryland, USA ; proceedings ; the 12th IEEE Sensors Conference.

[17] C. Shemelya et al., "Encapsulated copper wire and copper mesh capacitive sensing for 3-D printing applications," IEEE Sens J, vol. 15, no. 2, pp. 1280–1286, Feb. 2015, doi: 10.1109/JSEN.2014.2356973.

[18] M. Bodnicki, P. Pakuła, and M. Zowade, "Miniature displacement sensor," in Advances in Intelligent Systems and Computing, vol. 393, Springer Verlag, 2016, pp. 313–318. doi: 10.1007/978-3-319-23923-1_47.

[19] IEEE SENSORS 14. 2015 Busan et al., IEEE SENSORS 2015 November 1-4, 2015, Busan, South Korea : proceedings. IEEE, 2015.

[20] Y. Kim and K. Kim, "Near-field sound localization based on the small profile monaural structure," Sensors (Switzerland), vol. 15, no. 11, pp. 28742–28763, Nov. 2015, doi: 10.3390/s151128742.

[21] Transducer Research Foundation, Institute of Electrical and Electronics Engineers, IEEE Electron Devices Society, Alas. Transducers 18 2015.06.21-25 Anchorage, Alas. Transducers Conference 18 2015.06.21-25 Anchorage, and A. and M. 18 2015. 06. 21-25 A. International Conference on Solid-State Sensors, 2015 Transducers - 2015 18th International Conference on Solid-State Sensors, Actuators and Microsystems (Transducers) 21-25 June 2015, Anchorage, Alaska.

[22] S. Krachunov and A. J. Casson, "3D Printed Dry EEG Electrodes," Sensors (Basel), vol. 16, no. 10, Oct. 2016, doi: 10.3390/s16101635.

[23] I. Nassar, H. Tsang, and T. Weller, "3D printed wideband harmonic transceiver for embedded passive wireless monitoring," Electron Lett, vol. 50, no. 22, pp. 1609–1611, Oct. 2014, doi: 10.1049/el.2014.0769.

[24] K. Kadimisetty et al., "3D-printed supercapacitor-powered electrochemiluminescent protein

immunoarray," Biosens Bioelectron, vol. 77, pp. 188–193, Mar. 2016, doi: 10.1016/j.bios.2015.09.017.

[25] S. Y. Wu, C. Yang, W. Hsu, and L. Lin, "3D-printed microelectronics for integrated circuitry and passive wireless sensors," Microsyst Nanoeng, vol. 1, 2015, doi: 10.1038/micronano.2015.13.

[26] S. J. Leigh, C. P. Purssell, D. R. Billson, and D. A. Hutchins, "Using a magnetite/thermoplastic composite in 3D printing of direct replacements for commercially available flow sensors," Smart Mater Struct, vol. 23, no. 9, p. 095039, Sep. 2014, doi: 10.1088/0964-1726/23/9/095039.

[27] A. Frutiger et al., "Capacitive soft strain sensors via multicore-shell fiber printing," Advanced Materials, vol. 27, no. 15, pp. 2440–2446, Apr. 2015, doi: 10.1002/adma.201500072.

[28] B. An, Y. Ma, W. Li, M. Su, F. Li, and Y. Song, "Three-dimensional multi-recognition flexible wearable sensor: Via graphene aerogel printing," Chemical Communications, vol. 52, no. 73, pp. 10948–10951, 2016, doi: 10.1039/c6cc05910d.

[29] J. J. Adams et al., "Conformal Printing of Electrically Small Antennas on Three-Dimensional Surfaces," Advanced Materials, vol. 23, no. 11, pp. 1335–1340, Mar. 2011, doi: 10.1002/adma.201003734.

[30] J. U. Lind et al., "Instrumented cardiac microphysiological devices via multimaterial three-dimensional printing," Nat Mater, vol. 16, no. 3, pp. 303–308, Mar. 2017, doi: 10.1038/nmat4782.

[31] S. Ali, A. Hassan, G. Hassan, J. Bae, and C. H. Lee, "All-printed humidity sensor based on graphene/methyl-red composite with high sensitivity," Carbon N Y, vol. 105, pp. 23–32, Aug. 2016, doi: 10.1016/j.carbon.2016.04.013.

[32] N. Jeranče, N. Bednar, and G. Stojanović, "An ink-jet printed eddy current position sensor," Sensors (Switzerland), vol. 13, no. 4, pp. 5205–5219, Apr. 2013, doi: 10.3390/s130405205.

[33] J. Gao, J. Siden, H. E. Nilsson, and M. Gulliksson, "Printed humidity sensor with memory functionality for passive RFID tags," IEEE Sens J, vol. 13, no. 5, pp. 1824–1834, 2013, doi: 10.1109/JSEN.2013.2244034.

[34] D. B. Krklješ and G. M. Stojanovic, "An ink-jet printed capacitive sensor for angular position/velocity measurements," 3D Print Addit Manuf, vol. 16, no. 4, pp. 77–82, 2016, doi:

10.4316/AECE.2016.04012.

[35] D. Krklješ, D. Vasiljević, and G. Stojanović, “A capacitive angular sensor with flexible digitated electrodes,” Sensor Review, vol. 34, no. 4, pp. 382–388, Aug. 2014, doi: 10.1108/SR-11-2012-683.

[36] R. I. Haque, E. Ogam, C. Loussert, P. Benaben, and X. Boddaert, “Fabrication of capacitive acoustic resonators combining 3D printing and 2D inkjet printing techniques,” Sensors (Switzerland), vol. 15, no. 10, pp. 26018–26038, Oct. 2015, doi: 10.3390/s151026018.

[37] P. Maillard and A. Heinrich, “3D printed freeform optical sensors for metrology application,” Sep. 2015, p. 96281J. doi: 10.1117/12.2191280.

[38] B. Igrec, M. Bosiljevac, Z. Sipus, D. Babic, and S. Rudan, “Fiber optic vibration sensor for high-power electric machines realized using 3D printing technology,” Mar. 2016, p. 975410. doi: 10.1117/12.2211578.

[39] K. Willis, E. Brockmeyer, S. Hudson, and I. Poupyrev, “Printed optics,” in Proceedings of the 25th annual ACM symposium on User interface software and technology - UIST ’12, 2012, p. 589. doi: 10.1145/2380116.2380190.

[40] B. Polzinger, J. Keck, V. Matic, W. Eberhardt, and H. Kück, “D4.1 - Inkjet and Aerosol Jet® Printed Sensors on 2D and 3D Substrates,” Dec. 2020, pp. 566–569. doi: 10.5162/sensor2015/d4.1.

[41] J. Zhao, M. Liu, L. Liang, W. Wang, and J. Xie, “Airborne particulate matter classification and concentration detection based on 3D printed virtual impactor and quartz crystal microbalance sensor,” Sens Actuators A Phys, vol. 238, pp. 379–388, Feb. 2016, doi: 10.1016/j.sna.2015.12.029.

[42] Y. B. K. D. B. and N. F. de R. J. Courbat, “INKJET PRINTING ON PAPER FOR THE REALIZATION OF HUMIDITY AND TEMPERATURE SENSORS,” 2011.

[43] M. F. Farooqui, C. Claudel, and A. Shamim, “An Inkjet-Printed Buoyant 3-D Lagrangian Sensor for Real-Time Flood Monitoring,” IEEE Trans Antennas Propag, vol. 62, no. 6, pp. 3354–3359, Jun. 2014, doi: 10.1109/TAP.2014.2309957.

[44] E. Sauerbrunn, Y. Chen, J. Didion, M. Yu, E. Smela, and H. A. Bruck, “Thermal imaging using

polymer nanocomposite temperature sensors," physica status solidi (a), vol. 212, no. 10, pp. 2239–2245, Oct. 2015, doi: 10.1002/pssa.201532114.

[45]T. Yamada et al., "A stretchable carbon nanotube strain sensor for human-motion detection," Nat Nanotechnol, vol. 6, no. 5, pp. 296–301, May 2011, doi: 10.1038/nnano.2011.36.

[46] B. Dermeik and N. Travitzky, "Laminated Object Manufacturing of Ceramic-Based Materials," Adv Eng Mater, vol. 22, no. 9, p. 2000256, Sep. 2020, doi: 10.1002/adem.202000256.

[47] O. A. Mohamed, S. H. Masood, and J. L. Bhowmik, "Optimization of fused deposition modeling process parameters: a review of current research and future prospects," Adv Manuf, vol. 3, no. 1, pp. 42–53, Mar. 2015, doi: 10.1007/s40436-014-0097-7.

[48] T. Ching, Y. Li, R. Karyappa, A. Ohno, Y.-C. Toh, and M. Hashimoto, "Fabrication of integrated microfluidic devices by direct ink writing (DIW) 3D printing," Sens Actuators B Chem, vol. 297, p. 126609, Oct. 2019, doi: 10.1016/j.snb.2019.05.086.

[49] M. A. S. R. Saadi et al., "Direct Ink Writing: A 3D Printing Technology for Diverse Materials," Advanced Materials, vol. 34, no. 28, p. 2108855, Jul. 2022, doi: 10.1002/adma.202108855.

[50] F. Fischer, "F O R A 3 D W O R L D TM White Paper Determining which technology is right for your application FDM AND POLYJET 3D PRINTING."

[51] Y. Guo, H. S. Patanwala, B. Bognet, and A. W. K. Ma, "Inkjet and inkjet-based 3D printing: connecting fluid properties and printing performance," Rapid Prototyp J, vol. 23, no. 3, pp. 562–576, Apr. 2017, doi: 10.1108/RPJ-05-2016-0076.